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NONDESTRUCTIVE TESTING FOR FIELD WELDS: REAL TIME WELD QUALITY --ETC(U)
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NONDESTRUCTIVE TESTING FOR FIELD WELDS: REAL TIME WELD QUALITY MONITOR

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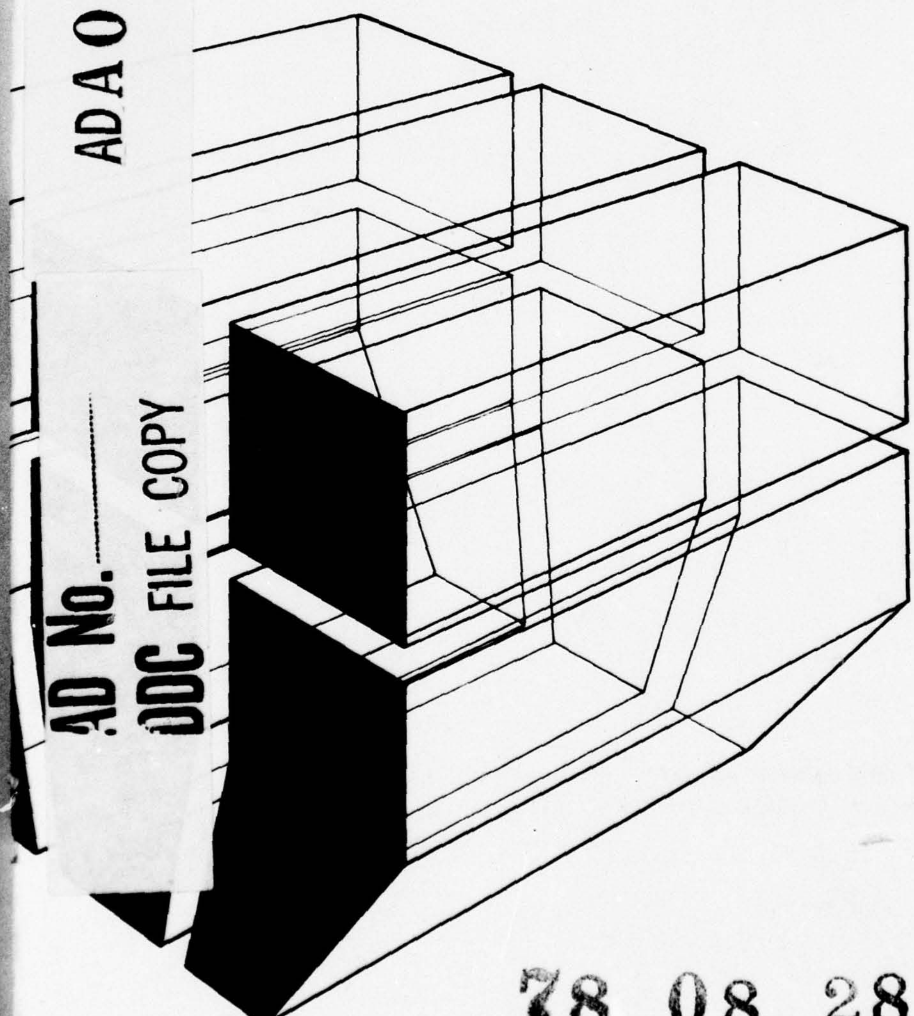

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This report describes part of a study to develop a field portable weld quality monitor. A real time weld quality monitor was configured and subjected to laboratory and field tests. Based on the tests, it was determined that the WQM design is adequate and has field applicability.

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FOREWORD

This investigation was conducted by the Engineering and Materials Division (EM), Construction Engineering Research Laboratory (CERL) for the Directorate of Military Construction, Office of the Chief of Engineers (OCE). The research was funded under Project 4A762719AT41, "Design, Construction and Operations and Maintenance Technology for Military Facilities"; Task 04, "Construction Systems Technology"; Work Unit 009, "Nondestructive Testing for Field Welds." The QCR is 1.06.004. Messrs. C. Damico and E. Hunt were the OCE Technical Monitors.

Dr. G. R. Williamson is Chief of EM. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

NONDESTRUCTIVE TESTING FOR FIELD WELDS:
REAL TIME WELD QUALITY MONITOR

1 INTRODUCTION

Background

During the welding process, changes in arc voltage, travel speed, and heat input can occur without the operator's knowledge. These changes can cause defects such as porosity, slag inclusions, incomplete fusion, and undercut in the deposited weld metal (Appendix A). The cost of locating and repairing these defects can be a major portion of construction costs; welding inspection can constitute 25 to 40 percent of the weld fabrication cost. In addition, weld defects decrease the service life of welded joints.

Consequently, it is necessary to monitor the welding parameters to detect, identify, and locate possible defects. A weld monitor with real time output would aid the inspector in designating suspect areas for nondestructive testing. To address this need, the U.S. Army Construction Engineering Research Laboratory (CERL) is conducting research to develop a field portable weld quality monitor (WQM).

In the initial phase of study,[1] the following requirements were established for the device. It should:

1. Monitor the three primary signals from the weld system: arc voltage, current, and travel speed; compare them to preset limits; and alert the operator if the limits are exceeded.

2. Calculate the heat input, nugget area, and cooling rate from the three primary signals; compare these values with preset limits; and alert the operator if these limits are exceeded.

3. Be field portable.

4. Interface easily with in situ welding equipment.

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[1] R. Weber, F. Kearney, and S. Joshi, *Development of Weld Quality Monitor*, Interim Report M-183/ADA027644 (U.S. Army Construction Engineering Research Laboratory [CERL], July 1976).

Essentially, the WQM is intended to provide a mechanism to merge the welding engineer's design intent with the actual field welding process.

Following development of these requirements, a prototype WQM was designed, fabricated, and tested using input from a fully automatic gas metal-arc (GMA) welding machine.[2] The automated GMA process was chosen to obtain close control and reproducibility of the welding variables for initial testing.

Appendix B describes the circuitry of the WQM.

Objective

The objectives of this phase of study were (1) to configure a portable, real time WQM system, and (2) conduct laboratory and field tests to determine the adequacy and field applicability of the design.

Future phases of the WQM study will aim at developing (1) suitable speed sensing systems for manual welding situations, (2) specific radiometric measurement techniques involving acoustic and thermal spectral analysis, and (3) digital processing features using microprocessors to facilitate programming the WQM.

Approach

The design of the prototype WQM developed in the earlier phase of study was modified to incorporate improvements indicated by actual welding situations in the laboratory. Hardware was assembled and packaged for field use.

In the transitional period from laboratory prototype to field prototype, personnel in Government and the private sector were consulted and their suggestions were used to further improve the unit.

The unit was then installed in a welding situation that would thoroughly test all modes of operation.

Mode of Technology Transfer

This study will impact on TM 5-805-7, *Welding; Design Procedures and Inspection* (Department of the Army, 15 March 1968).

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2 R. Weber et al, Interim Report M-183.

2 LABORATORY TEST

Procedure

Each channel of the laboratory prototype monitor was individually tested with a variable signal similar in current and voltage level to the signal from a welding machine. The limits for each channel were set, and the test voltages were varied to simulate changes in the primary signals. When the status lights indicated that the limit had been exceeded, the test voltage was compared to the preset limit value to check the accuracy of the comparator circuit.

After each channel had been tested successfully, the three simulated primary signals were fed into the monitor simultaneously. The limits were again set and the input voltages varied. All circuits, including the analog computer section, were checked for accuracy and reproducibility.

The monitor was then connected to the CERL welding machine to test the circuitry with actual signals. After the limits were set, a welding arc was established on a test plate.

Results

Results of the laboratory testing showed that all channels performed satisfactorily, both independently and in conjunction with each other. The warning lights were triggered when the input signal exceeded the limits set by the reference signal, and no difficulties were encountered when the limit span was changed.

While investigating the signals of the three parameters (voltage, current, and speed), it was found that the voltage and amperage signals contained spurious noise signals. These signals were removed by (1) incorporating filters in the data channel to eliminate the peaks and smooth out the signals, thus reducing the chance of damage to components, and (2) replacing the shunt as the amperage signal source with a Hall effect solid state transductor. (The advantage of using the transductor is that it is not directly connected to the welding cable as the shunt is; instead, it fits around the cable and measures the magnetic field generated by the current passing through the cable.) The transductor minimized amperage transient signal problems; filters were installed in all channels for field contingencies.

The modifications indicated by the laboratory testing program were incorporated into the monitor before field testing. The system assembled for field testing is shown in Figure 1.

3 FIELD TEST

Site Selection

The two general types of welding operations considered for field testing were shop fabrication, which uses automated welding equipment, and field fabrication/repair, which involves manual or semi-automatic welding and is more dependent on the operator's subjective judgment.

In addition, it was decided that field tests would be more conclusive if the weld quality monitor were used in conjunction with some other form of NDT. Two sites were available that offered these combinations: Flint Steel Corporation, Tulsa, OK, and a hydroelectric turbine shaft repair job at Ozark Hydroelectric Plant, Ozark, AK. The field repair job at Ozark Power Plant was chosen since it would entail situations that could not be simulated during the CERL laboratory evaluations. It was felt that the time and space constraints of the field repair* situation would assess the unit's adaptability most rigorously. In addition to the hardware evaluation, the field test would provide an opportunity for welding personnel from industry to appraise the WQM.

Test Operations

The WQM and auxiliary equipment were transported from CERL to the Ozark plant in a conventional automobile with no special handling. The equipment was set up by maintenance personnel and was ready for operation in less than 1 day.

The WQM was set up remote from the repair location, approximately 50 ft (15 m) from the access door (Figure 2). Figure 3 shows the unit connected for testing.

The Hall effect current transductor is shown in Figure 4. Installation of this device involves simple disconnection and reconnection of one of the leads from the welder power unit; no hard wiring is required.

The welding operation in Figure 5 shows the WQM voltage sensing lead attached to the welding cable leading to the welding gun. The lead does not encumber the operator in any way.

*Repair welding procedure is given in Appendix C.

Since no speed measurement system was available for this test, a precision voltage source was used to provide an equivalent speed signal to compute heat input and nugget area. For this mode of operation, a voltage corresponding to a particular welding speed is input to the analog computer module to compute heat input and nugget area (Equations A1 and A3, Appendix A). For example, if the analog module were scaled for 1 volt = 1 in./min, then a 6-volt signal from the precision voltage source would be input for a welding speed of 6 in./min.

A typical voltage and current time trace obtained from the WQM is given in Figure 6. These signals were taken at the output of the signal conditioners before filtering for inputting the comparators. As can be seen, the signal is not distorted and shows the response of the sensors to the voltage and current variations occurring in the arc. Because the parameter data content is preserved in the tranduction and conditioning process, several data utilization options are possible -- from simple alarms to adaptive control systems.

Results

Installation

The central unit and associated sensors were interconnected and energized without disrupting the welding contractor or requiring welding equipment modification. This verified the adaptability and flexibility of the design objective. Installation of the system was accomplished by a ceramic engineer; an electrical engineer was not required.

Operation and Data Interpretation

The WQM was operated by nonelectronic personnel (a welding engineer) with minimal instruction. The data display and printout were understandable to both Corps and contractor personnel.

Troubleshooting

During the start up of the WQM, erratic operation was indicated by the visual display; the modular packaging method enabled the problem to be diagnosed and repaired rapidly by interchanging modules. Again, this was accomplished by nonelectronic personnel using predefined troubleshooting procedures.

4 CONCLUSION

A real time WQM was configured and subjected to laboratory and field tests. Based on the tests, it was determined that the WQM design is adequate and has field applicability.

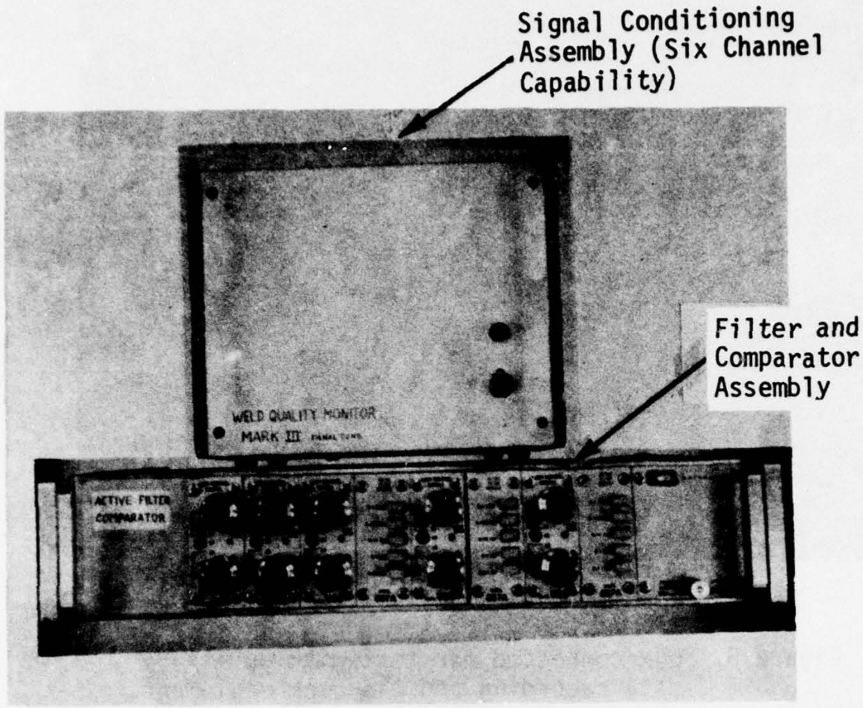


Figure 1. Modified prototype weld quality monitor.

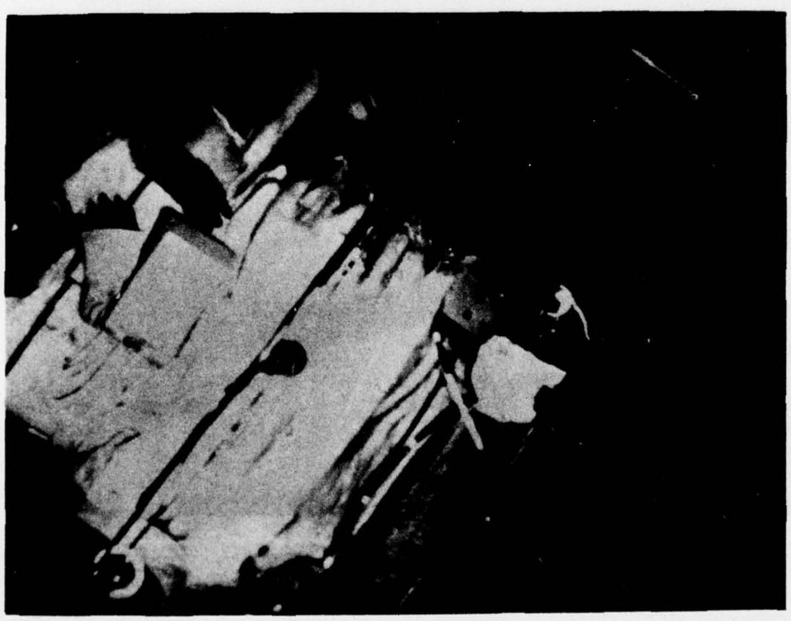


Figure 2. Ozark shaft weld joint.

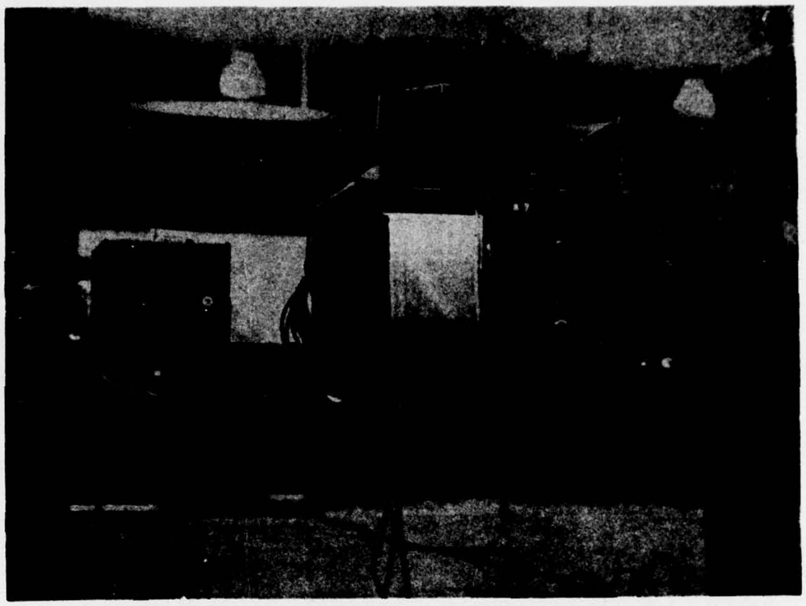


Figure 3. WQM connected for test with auxiliary data recording and playback equipment.

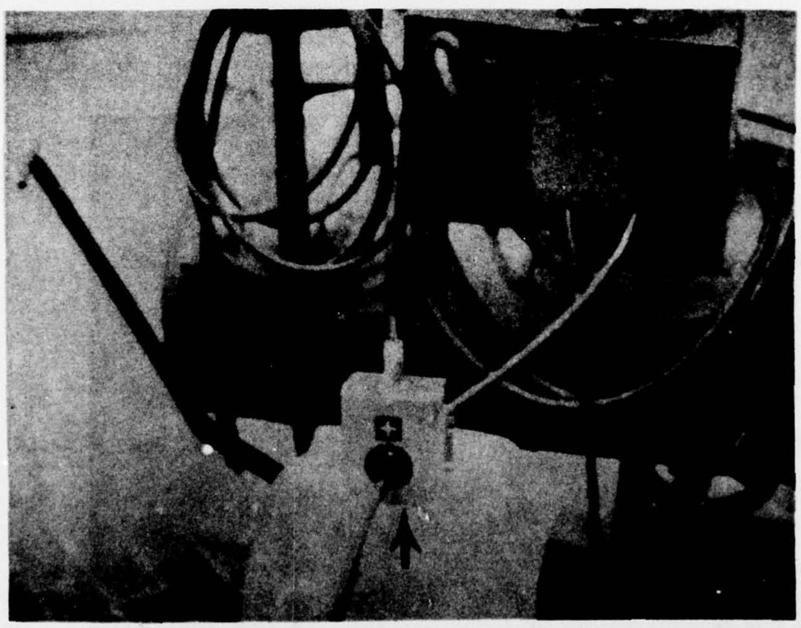
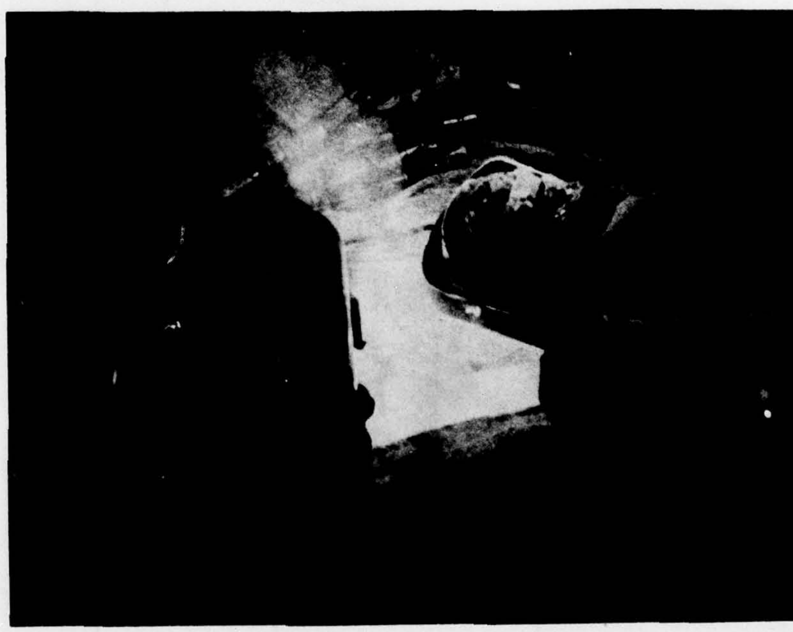


Figure 4. Hall effect current transductor.



WQM Voltage
Sense Lead

Figure 5. WQM field test; WQM arc voltage sense lead attached to welding stick cable.

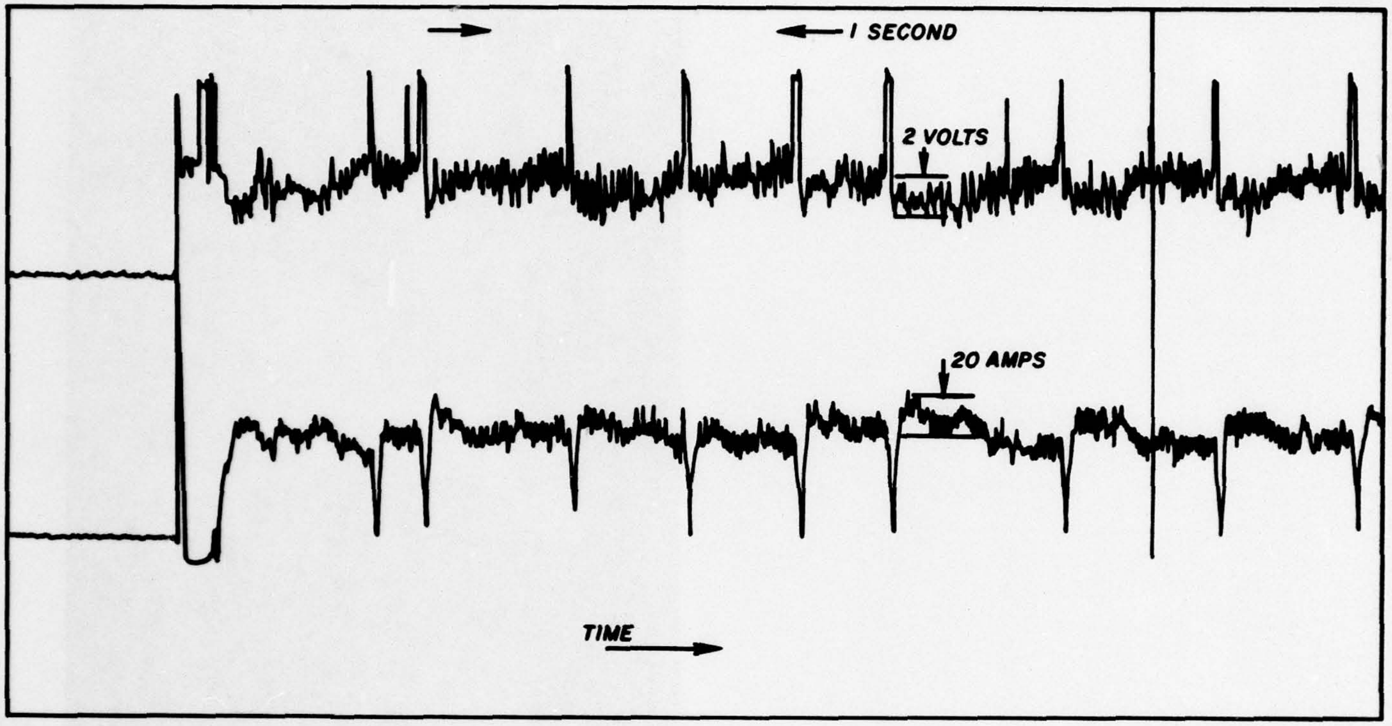


Figure 6. Voltage current trace obtained from the WQM for shaft repair weld.

APPENDIX A:

FACTORS AFFECTING WELD METAL MECHANICAL PROPERTIES

Defects

Changes in the welding parameters of arc voltage, travel speed, and heat input can cause several types of defects in the deposited weld metal.

Porosity is a void or gas pocket trapped in solidifying weld metal. The reduced solubility of the gas in the metal caused by the decreasing temperature forces the gases out of solution. The gases are originally introduced either by poor shielding, which entrains air, or by chemical reactions in the molten weld metal. With stick electrodes, too long an arc resulting from excessive arc voltage can reduce the shielding effectiveness, thus introducing gas.

Slag inclusion is the entrapment of an oxide or other nonmetallic material under the weld bead. The major source of slag is the coatings on stick electrodes. This defect is related to heat input.

Incomplete fusion is the failure of adjacent layers of the weld metal or weld base plate to fuse. Incomplete fusion may result when the adjacent metal is not heated to the melting point because of insufficient heat input.

An *undercut* is a groove melted into the baseplate at the toe of the weld and is caused primarily by excessive *travel speed* in relation to the welding current.

In addition to the defects caused by improper control, the heat generated by the welding process can cause the following changes in the base metal:

1. Grain coarsening
2. Softening (annealing effects)
3. Hardening (phase precipitation or transformation)
4. Segregation of constituents
5. Grain boundary melting
6. Loss of ductility

7. Loss of toughness

8. Residual stresses causing distortion or cracking.

The type of change which occurs depends on the chemical composition of the base metal and electrode and the heat history of the base plate.

In the two commonly used field welding processes--shielded metal-arc (stick electrodes) and gas metal-arc (bare-wire)--the source of heat for melting the materials is an electric arc. Control of the arc parameters will control the amount of heat generated, the length of time at an elevated temperature, and the cooling rate of the weld zone.

Base Metal Microstructure

The cooling cycle after a weld pass determines the microstructure of the weld metal and the heat-affected zone. With fast cooling rates, some steels become very hard because of a martensitic transformation. If the cooling rate is sufficiently slow, the metal may be more ductile and the structure ferritic and pearlitic. The type of steel generally determines which of these structures is desired. For low-carbon and low-alloy steels, the pearlitic structure is desirable, while for high-strength quenched and tempered steel, the martensitic structure is desirable.

Martensite is undesirable in low-carbon and low-alloy steels designed for yield strengths less than 80 ksi (552 MN/m^2) because of its hardness and low solubility for hydrogen at ambient temperatures. The combination of characteristics increases the likelihood of hydrogen cracking in the joint. Use of low-hydrogen stick electrodes and the gas metal-arc welding system reduces this tendency toward hydrogen-induced cracking.

Cooling Rate Control

Control of the cooling rate is essential in preventing undesirable microstructure in the weld and heat-affected base plate. A mathematical combination of arc voltage, current, and travel speed known as heat input (HI) has been used as a means of controlling cooling rate for many years. The equation for calculating heat input is

$$\text{HI (J/in.)} = \frac{\text{Voltage x Amperage x 60}}{\text{Travel Speed (in./min.)}} \qquad \text{(Eq A1)}$$

The normal maximum has been 55,000 to 60,000 J/in. (21 654 to 23 622 J/cm) for the field processes mentioned above. Another means of controlling cooling rate has been preheat treatment. Dorschu[3] has shown that the relationship between heat input, preheat temperature, and cooling rate is:

$$CR = \frac{m\,(T-T_o)2}{HI} + c \qquad \text{(Eq A2)}$$

where CR = cooling rate
T = test temperature, 1000°F (538°C)
T_o = preheat temperature
m,c = constants
HI = heat input (kJ/in.)

Eq A2 indicates that the higher the preheat temperature and heat input, the slower the cooling rate.

Shultz and Jackson[4] have shown that the cross sectional area of the weld bead is a useful indicator of weld metal mechanical properties and that a relationship exists between the area and cooling rate. They also found that arc voltage has little or no effect on the nugget area and cooling rate. The relationship that Shultz and Jackson have developed for nugget area, arc current, and speed is

$$na = 122 \times 10^{-7} \frac{i^{1.55}}{S^{.0903}} \qquad \text{(Eq A3)}$$

where na = nugget area (sq in.)
i = arc amperage
S = arc travel speed (in./min.).

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[3] K. E. Dorschu, "Control of Cooling Rates in Steel Weld Metal," *Welding Research Supplement* (February 1968).

[4] B. L. Shultz and C. E. Jackson, "Influence of Weld Bead Area on Weld Metal Mechanical Properties," *Welding Research Supplement* (January 1973).

APPENDIX B:

CIRCUIT DESCRIPTION

Figure B1 is a block diagram of the weld quality monitor showing the input signals from the welding arc. These signals are conditioned to standard values and sent to the comparator module, which compares the input signals with a set of limit signals.[5] If the input signals are too high or low, the appropriate alarm is triggered. The input signals are also transmitted to the analog computer module for calculation of the heat input, cooling rate, and nugget area. The calculated values are then compared to reference signals and the appropriate alarm is triggered if needed.

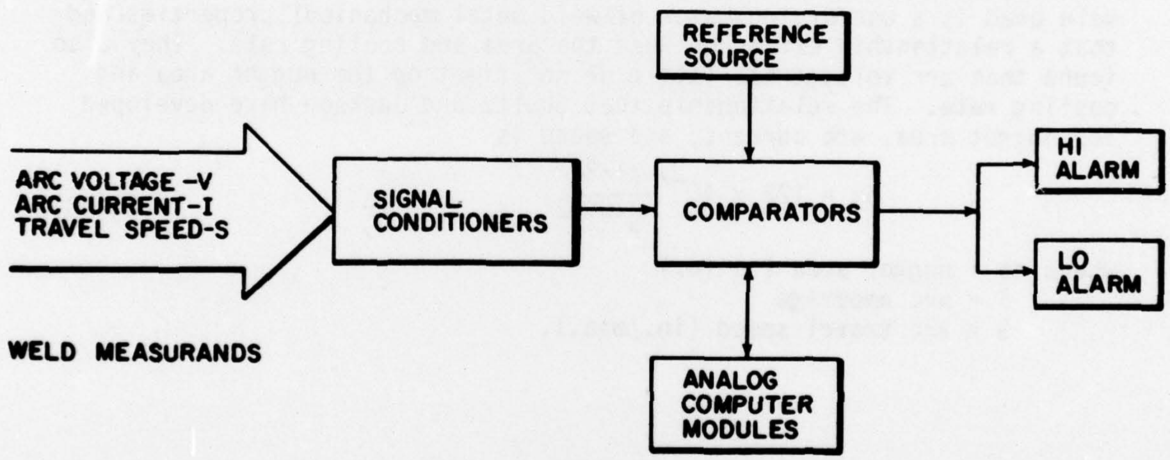

Figure B1. Block diagram of weld quality monitor.

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5 R. A. Weber and C. E. Jackson, *Review of Weldability of Construction Materials*, Interim Report M-168/ADA027383 (CERL, 1976).

APPENDIX C:

WELD REPAIR PROCEDURE -- OZARK HYDROELECTRIC SHAFT

Parameters

Process: SMAW
Filler Material: E7018

Electrode Diameter:	1/8 in. (.3mm)	5/32 in. (4mm)
Current Range:	115-165 amps	150-220 amps
Voltage Range:	21-24 volts	22-25 volts

Polarity: Direct current-electode positive
Preheat Temperature: 300°F (149°C) min.
Interpass Temperature: 350°F (178°C) max.
Postheat: 300°F (149°C) 6 hours

Heat input $\dfrac{\text{Voltage x Amperage x 60}}{\text{Travel Speed}}$ = 40 to 55 J/in.

Technique (Figure C1)

Check root pass temperature before welding beams.

1. The root pass shall be deposited using a back step welding technique; root should be nondestructively evaluated by some method before welding over.

2. Block welding shall also be employed to minimize transverse weld shrinkage.

3. Each weld bead shall be peened to control distortion. Peening of the first and final layers is prohibited.

4. The peening tool shall be ground to eliminate any sharp edges.

5. The air pressure used to drive the peening tools shall fall within a 95 to 100 psi pressure range.

6. An inside micrometer shall be used to measure between reference blocks for monitoring distortion while welding. These measurements may be taken only when all four heat zones are within the preheat and interpass temperature range, and the variance in temperature from any one zone to any other zone does not exceed 20°F (7°C).

7. The joint shall be welded at least one layer above flush and magnetic particle inspected.

8. During the 6 hour postheat at $300^{o}F$ ($149^{o}C$), the reinforcement may be removed by grinding. The grinding marks must be parallel to the shaft axis.

9. A final inspection shall be performed by magnetic particle testing and ultrasonic testing, 24 hours after the weld has cooled to an ambient temperature.

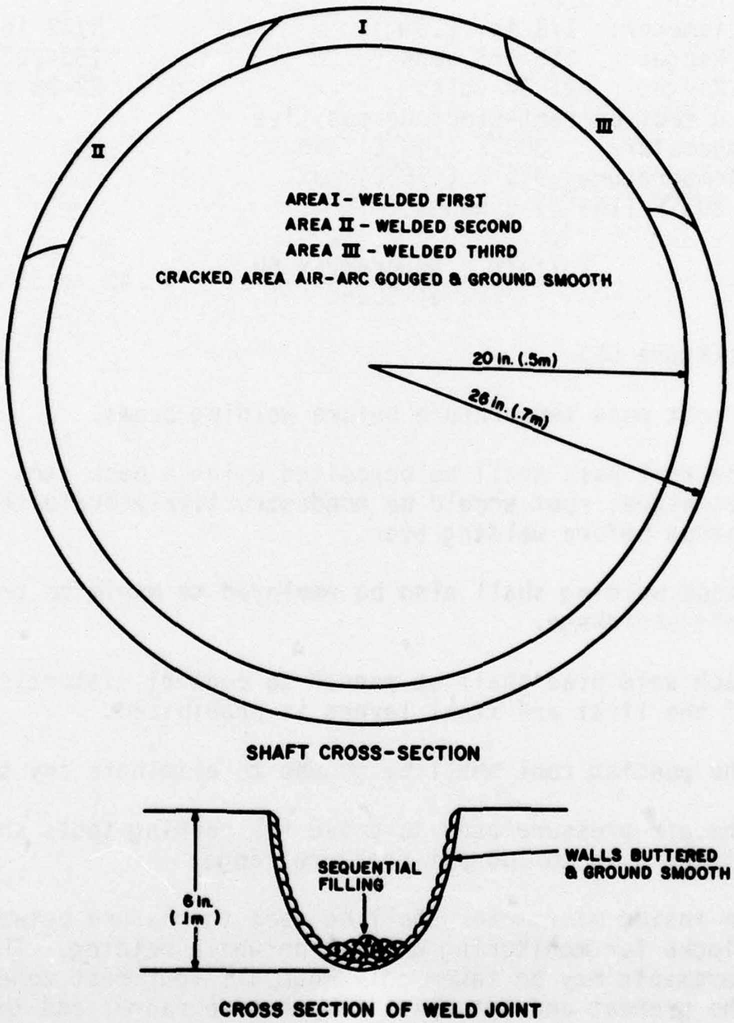

Figure C1. Cross sections of shaft and weld joint.

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